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# THE BOREHOLE SLEEVING TEST METHOD OF RESIN ANCHORED ROOF BOLT INSTALLATIONS

Kent McTyer<sup>1</sup>, David Evans<sup>2</sup>, Guy Reed<sup>1</sup> and Russell Frith<sup>1</sup>

**ABSTRACT:** Resin anchored roof bolts are the basis for the primary roof support system of every underground coal mine in Australia. However, the negative influences of uncured resin and resin loss due to installation pressure are common problems despite more than 30 years of product development. The current study details a surface testing method that installs a commonly used roof bolt into lengths of PVC pipe. Results were gathered in two ways, instrumentation measured bolt displacement and rotation speed and back-pressure during installation. The PVC was then cut open to assess the quality of the resin anchor. Comparative testing was undertaken on two resin cartridges commonly used in Australia: 2:1 mastic-to-catalyst resin and 15:1 mastic-to-catalyst resin. The tests were performed in 28 mm and 30 mm internal diameter PVC pipes to simulate a range of underground roof conditions. Data analysis shows the influence of borehole diameter, mastic-to-catalyst ratio and insertion pressure development on resin anchor reliability.

## INTRODUCTION

Resin-anchored roof bolts are used for primary roof support in every Australian underground coal mine. However, the efficacy of the resin-anchored roof bolt system has been found to be compromised in many Australian and New Zealand underground operations (Campbell and Mould, 2003; Craig, 2012).

A number of studies from Australia, New Zealand and the United States of America (US), as outlined below, have been conducted into the various limitations of resin-anchored roof bolts over the past 25 years. These include: gloving (where the polyester film cartridge wrapper remains intact around significant sections of the bolt and resin); uncured resin (particularly in the upper section of bolt); and the development of very high pressure in the uncured resin during installation. This paper describes recent ACARP-funded research into two factors: the proportion of uncured resin and the development of pressure in the resin during installation.

## PREVIOUS RESEARCH - INSTALLATION PRESSURE

Inserting a length of roof bolt through a resin cartridge into a drill hole can create significant pressure in the resin system. The pressure developed is a function of a number of factors including drill hole diameter, rebar diameter, drill hole depth, resin length and viscosity, insertion rate, and the maximum thrusting force that can be delivered by the bolting rig. Research has shown that this pressure can cause both hydraulic fracturing of the roof strata and resin injection into pre-existing strata voids, potentially damaging the roof strata. Pressure can also lead to a reduction in the length of the bolt that is encapsulated in resin, thereby comprising the bolt's effectiveness.

In US studies, the measured peak installation pressure ranged from 27-34 MPa (Compton and Oyler, 2005) and 24-48 MPa (Giraldo, *et al.*, 2006). Giraldo found that as annulus area was increased - by increasing borehole diameter for a given bolt diameter - the peak pressure reduced. Pettibone (1987) found that the installation pressure developed in the resin was sufficient to split (hydraulic fracture) 31 MPa concrete. Research using bolts recovered by overcoring (Campbell and Mould, 2003; Compton and Oyler, 2005; Craig, 2012) found evidence of the hydraulic injection of resin into the strata surrounding the drill hole. This resin injection was observed to a distance of 100 mm from the drill hole in the Campbell and Mould (2003) study. The underground trial by Compton and Oyler (2005) found that resin losses - averaging 40% of the total resin volume - occurred in weak roof strata. These losses were inferred to result from resin injection into either existing fractures or fractures created by the installation pressure. Underground studies of full resin encapsulated bolts found that increasing the annulus area resulted in a reduction in resin loss from 30% (Giraldo, *et al.*, 2006) and 27% (Craig, 2012) to 0%.

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A conflict becomes apparent because minimising the resin annulus has been shown to increase the load-transfer properties of an encapsulated roof bolt. However, this also directly reduces the amount of bolt encapsulation via the mechanisms just described. Therefore, a solution to maximise load transfer and resin encapsulation along the bolt will represent a significant improvement in roof bolting effectiveness.

### **PREVIOUS RESEARCH - UNCURED RESIN**

Adequate resin mixing relies on both the satisfactory shredding of the polyester film that contains the mastic and catalyst compartments and sufficient mixing of the two components to promote a uniform resin and mastic compound. When this occurs the resulting resin compound is typically fully cured, hard and homogeneous. Conversely, inadequate resin mixing results in a partially cured, soft and non-uniform resin.

The integrity of resin-anchored roof bolts relies on the quality and consistency of the cured resin. Uncured resin offers no load transfer to the strata (Campbell and Mould, 2003). The 15:1 mastic:catalyst resin cartridges, used commonly in Australia, have been found to be susceptible to uncured resin in the upper portion of the bolt. Campbell and Mould (2003) found that of 79 overcored "run of mine" bolts, the average uncured resin length was 245 mm (with a range from 0 - 750 mm).

The high incidence of uncured resin was found to be caused by the radial expansion of the resin cartridge as the installation pressure increased. This forces the catalyst section hard against the wall of the bolt hole and allows the bolt to pass through the resin without piercing the small catalyst compartment. In the USA, Compton and Oyler (2005) tested 24 overcored bolts using the 2:1 mastic:catalyst resin cartridges commonly used in the US market. They found no evidence of uncured resin, and concluded that both mastic and catalyst compartments of the 2:1 resin are more likely to be torn during bolt installation than the 15:1 resin used in Australia.

### **CURRENT ACARP STUDY (PROJECT C21023)**

The ACARP study aims firstly, to develop a new, highly controlled, surface-testing method designed to simulate underground resin bolt installations while also allowing rapid, multiple tests. Underground field trials are subject to both the naturally occurring geological variability present in the bolted interval, and the variability in the installation process caused by different drilling hardware, machinery and operators. The method aims to both remove these sources of variability and to provide a larger, and therefore more robust, data set than has been possible with previous methods.

Secondly, instrumentation was used to accurately record the bolt displacement, bolt rotation, and installation pressure over time. The data was collected following manufacturers specifications using typical Australian bolts, resin cartridges and drill hole diameters. This study aims to add to the research previously undertaken on US roof support hardware by providing data that is more relevant to Australian bolting practices.

Thirdly, this study aims to observe and compare 15:1 and 2:1 resin systems during bolt installation to further understand the degree of uncured resin present in fully encapsulated roof bolts used in Australian underground coal mines. The method design aimed to allow observation of the degree of uncured resin in test bolts under controlled conditions for the first time.

### **SURFACE TESTING**

The testing used a commonly available 1.8 m long M24 bolt with a core bar diameter of 21.7 mm and major bar diameter of 23.2 mm. Two resin types were tested: the catalyst-to-mastic ratio was either 15:1 or 2:1. Resin length was 1000 mm and resin diameter was 23 to 24 mm in all tests. Both resins were two-speed 50% fast- and 50% slow-set cartridges. These products were chosen to compare the 15:1 resin-anchored roof bolt system commonly used in Australian coal mines, with an alternative (2:1 resin) that could readily be brought into use without major changes in bolting hardware or installation practices.

Two drill hole diameters were assessed: 28 mm and 30 mm. This was made possible by using PVC pipe sleeves with different wall thickness. These diameters were chosen to represent the drill hole

diameters found underground that typically form when drilling with 27 mm and 28 mm drill bits. The 30 mm internal diameter is considered representative of coal mines with either weak roof lithologies such as claystone or coal, or immediate roof strata subject to elevated horizontal stress conditions that can cause substantial drill hole overbreak.

Bolts were installed according to manufacturer's recommendations on a specially devised hydraulic bolting rig, albeit one that may not be as powerful hydraulically as those commonly available on underground continuous miners' in Australian operation. The rig was fitted with instrumentation to measure bolt rotation, bolt travel, and pressure generated during bolt insertion. A total of 91 bolt installations were undertaken as part of the surface installation testing program.

### **RESIN MIXING EXPERIMENTATION BACKGROUND**

Traditionally, the simulation of resin roof bolt installations has been conducted into media such as sandstone core samples, internally grouted steel pipes, or into heavy walled steel tubing. For sandstone cores and grouted pipes, a pilot guide hole and then a final bore hole are pre-drilled to provide the desired test hole diameter. For steel tubing, often a crude thread or rifling is cut along the internal wall of the bore to simulate surface roughness commonly associated with underground drilling. There was often great focus on the surface properties and compressive strength of the media used in an effort to simulate underground lithology and performance. These traditional methods are useful for laboratory trials involving load transfer tests, where the steel element of the roof bolt was loaded and the resin bond strength was tested between the steel element and the media.

However, to visually assess the effectiveness of resin mixing, these traditional methods are in fact a hindrance. For sandstone and grouted pipes, the media has to be progressively removed to manually expose the outer surface of the resin annulus. The outer resin surface is mechanically damaged during removal of the media and the true interface can be difficult to precisely determine. As a result of this damage, visibility of the outer resin annulus was unclear and it was difficult to fully assess the effectiveness of resin mixing. The removal process was also laborious and time-consuming.

### **BOREHOLE SLEEVING – A NEW EXPERIMENTAL METHODOLOGY**

In order to overcome these issues, a new methodology was developed which provides a comprehensive visual assessment of resin curing under realistic bolt installation conditions. The new methodology involved internal sleeving of the test borehole, where the sleeve was readily removable after each resin installation test was completed. The internal sleeve was neatly constrained within a dimensionally rigid, heavy walled steel pipe to prevent any swelling of the sleeve during the test. As such, comparatively weak plastic materials such as PVC could be used for the internal sleeve, with bolt insertion and resin mixing pressures constrained by the outer heavy walled steel pipe. A closed-end cap assembly at the top of the sleeve prevented any resin loss from the test pipe system, and therefore, allowed resin backpressures to be developed. An open end cap at the bottom of the jig retained the sleeve in position prior to insertion of the bolt.

### **BENEFITS OF THE NEW EXPERIMENTAL METHODOLOGY**

The benefits of the new methodology were two-fold. The first was the ability to conduct rapid, multiple test installations, which produced a large data set of test results under controlled, repeatable and measureable conditions. As each test was completed, the end caps containing the sleeve were removed and the completed test specimen - sleeve and resin bolt assembly - were readily removed as a single piece from within the steel outer pipe. A new sleeve was then inserted, the end caps were replaced and a new test was ready to be conducted. Using this method, up to 49 installations were conducted in a day.

The second major benefit was the ability to conduct a comprehensive visual inspection of the resin annulus for each completed test sample. The PVC was cut with an angle-grinder along the length of the bolt. The PVC and resin were cut through to the rebar to facilitate removal of the bolt and resin intact from the sleeve. This method allowed for observation of the degree of resin curing through the entire thickness of the resin annulus within the saw cuts. The remainder of the resin visual examination can be made around 360 degrees of annulus surface and along the full length of the bolt. Areas of poor resin curing were therefore immediately exposed.

## RESULTS - INSTALLATION PRESSURE

The instrumentation used here produced accurate measurements of installation force, bolt displacement and rotation speed. Together with a known bore diameter, these measurements reduce the number of unknown factors that exist when installing a resin-anchored roof bolt in an underground setting.

Table 1 shows that the peak pressure measured in the two previous US studies were higher than those measured in the current study. This could be due to a number of factors, including typically higher resin viscosity used in US resins (Craig, 2012), installation method (i.e. push to back rather than spin during insertion) and the greater hydraulic capacity of the drill rigs in the US studies.

**Table 1 - Resin-anchored roof bolt insertion pressure results from this study and previous studies**

STUDY	Major Bar Diameter	Hole Diameter	Annulus	Insertion Rate	Peak Pressure	Installation Method
Compton and Oylar (2005)	18 mm	27 mm	4.5 mm	127 mm/s	34.5 MPa	Push to back then spin
	21.5 mm	27 mm	2.75 mm	Stalled	N/A	
Giraldo <i>et al.</i> (2006)	21.5 mm	27 mm	2.75 mm	180 mm/s	45 MPa	Push to back then spin
	21.5 mm	27 mm	2.75 mm	115 mm/s	43 MPa	
	21.5 mm	32 mm	5.25 mm	180 mm/s	45 MPa	
	21.5 mm	32 mm	5.25 mm	115 mm/s	33 MPa	
	24 mm	35 mm	6 mm	180 mm/s	34 MPa	
	24 mm	35 mm	6 mm	115 mm/s	24 MPa	
McTyer <i>et al.</i> (2014)	23 mm	28 mm	2.5 mm	145 mm/s	18 MPa	Spin during insertion
	23 mm	30 mm	3.5 mm	170 mm/s	14 MPa	

In this study, the maximum available thrust force of the drill rig was achieved for both 28 mm and 30 mm diameter pipe tests. The average insertion rate was found to be slower during the 28 mm tests, with a slowing rate of insertion being found to coincide with the period over which elevated pressure was recorded. A "dry run" without resin was measured to take approximately 5 seconds to travel 1000 mm (i.e. 200 mm/s). When resin was used, the insertion rate slowed to 170 mm/second for a resin bolt in a 30 mm diameter pipe and to 145 mm/second in a 28 mm diameter pipe (Table 1). These results indicate that the drill rig used was not able to maintain the same insertion rate throughout the full bolt insertion stage, probably because of its limited hydraulic capacity. This finding was not significant to the results but does suggest that higher peak insertion pressures (similar to those found in the US studies) would inevitably be reached with a more powerful drill rig.

For the 28 mm internal diameter pipe samples (Figure 1), an average of 18 MPa of pressure was maintained for a period of approximately 4 seconds. Most importantly, this elevated magnitude of pressure occurred during the final 500 mm of the bolt insertion.

The samples in the larger 30 mm internal diameter pipe (Figure 2) had a lower average pressure of 13 - 14 MPa but were observed to have a fundamentally different trajectory. Specifically, the period of peak pressure was considerably shorter, approximately 0.5 seconds, and was only present during the final 100 mm of bolt insertion.

## RESULTS - RESIN CURING

Observation of resin curing was made along the entire resin encapsulation length. Individual areas of uncured resin were measured and a total recorded along the axial length of the bolt. The total length of uncured resin was recorded for three sections of the bolt. The three sections of bolt were the upper (0 - 300 mm), middle (300 - 800 mm), and lower (800 - 1700 mm). The amount of uncured resin was recorded for both all the way around the bolt circumference and partially around the circumference. Two distinct uncured resin types were observed.

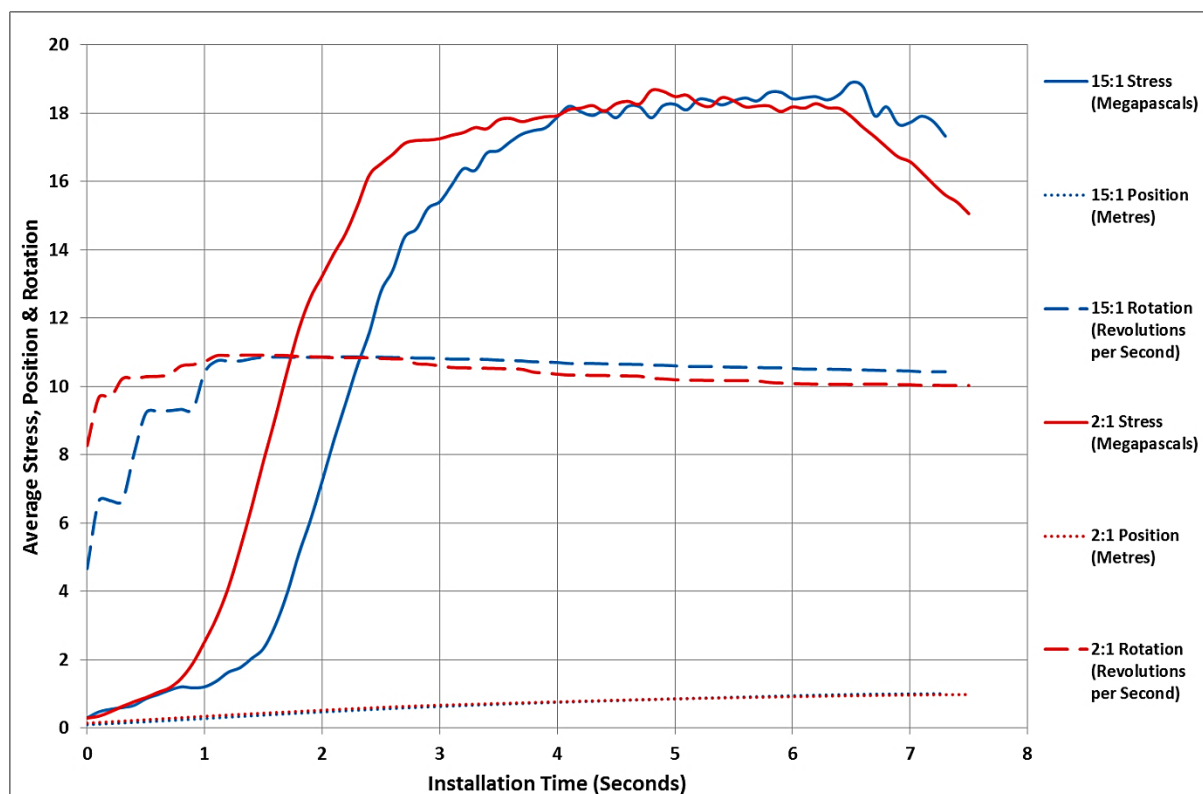


Figure 1 - Stress, position and rotation averages from 28 mm internal diameter pipe installations

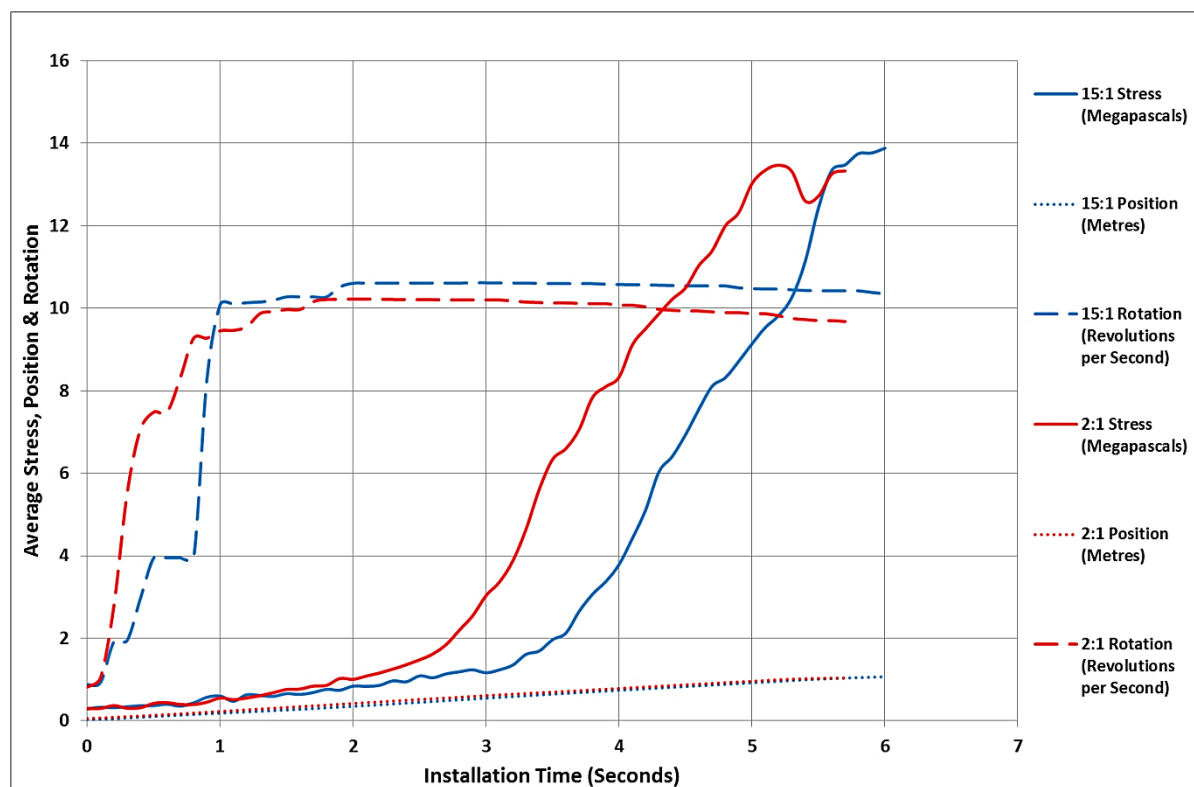


Figure 2 - Stress, position and rotation averages from 30 mm internal diameter pipe installations

The first was wet mastic found throughout the entire thickness of the resin annulus. This appears to occur when the bolt does not pierce the catalyst compartment. There were no examples of this observed in the 2:1 resin. Full-annulus uncured resin was not observed in the 2:1 resin because it is a geometric impossibility for the bolt to not pass through both the mastic and the catalyst compartment during bolt insertion. However, four examples of this type of uncured resin were observed in the 15:1



resin samples (approximately 8% of samples). This may be possible because of the mechanism of radial expansion of the resin cartridge (Campbell and Mould, 2003). This mechanism allows the bolt to reach the back of the hole without piercing the catalyst compartment. The result was typically wet mastic around the full circumference of the bolt (Figure 3).



**Figure 3 - 15:1 resin installed in a 30 mm ID pipe (above) and in a 28 mm ID pipe (below)**

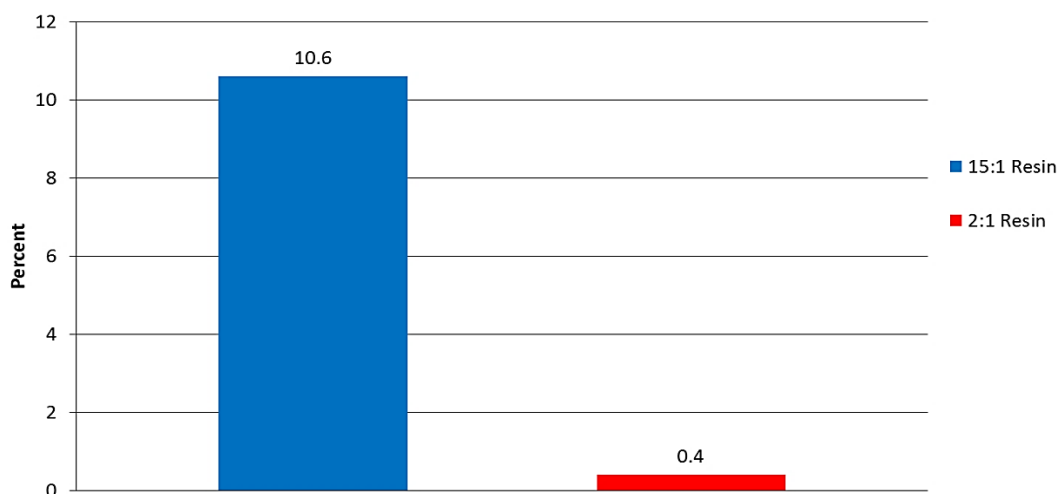
Secondly, uncured resin was observed in the channels cut through the PVC and resin to the rebar. The cuts were made more than 24 hours after bolt installation. Uncured resin was found to flow out from the annulus beneath a hard cured “crust” of resin (Figure 4). While the impact of these uncured sections under a hard crust has not been quantified in terms of load transfer, it is reasonable to assume that load transfer properties would be negatively affected.



**Figure 4 - Resin “flow” into the saw-cut channel of 15:1 resin (above) and 2:1 resin (below)**

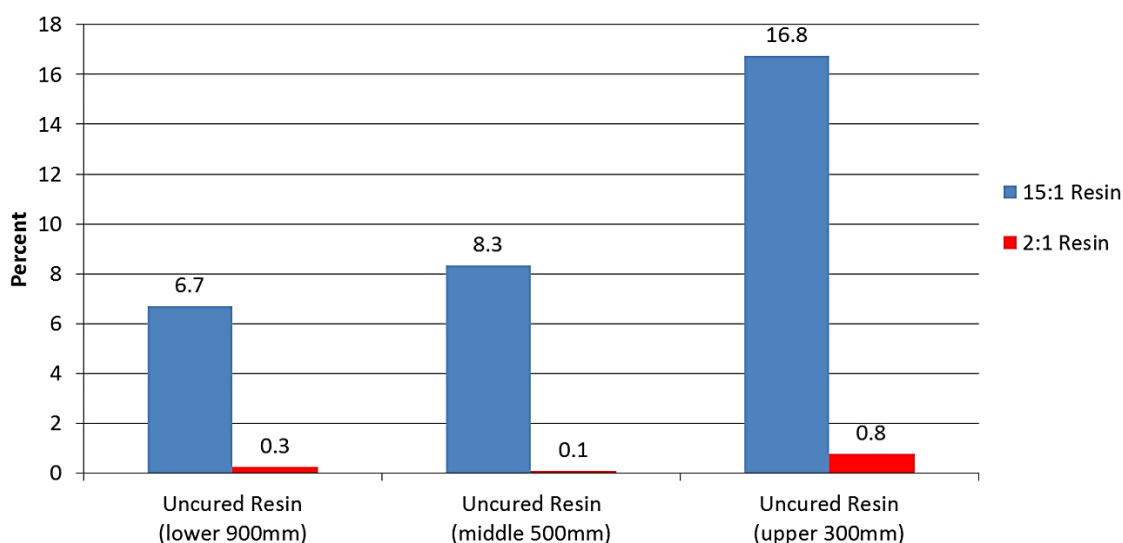
Analysis of the results was undertaken on a total of 91 installations: 15:1 resin in 28 mm diameter pipe (n=34); 15:1 resin in 30 mm diameter pipe (n=14); 2:1 resin in 28 mm diameter pipe (n=30); and 2:1 resin in 30 mm pipe (n=13). The data collected was further separated into three categories representing the upper (0-300 mm), middle (300-800 mm), and lower (800-1700 mm) section of the total encapsulation length. The results are reported as the average percentage of uncured resin.

Figure 5 shows the average uncured resin percentage for 2:1 and 15:1 resins measured along the encapsulated length of the bolt for both 28 mm and 30 mm internal diameter pipe installations.



**Figure 5 - Average percentage uncured resin observed for 15:1 and 2:1 resins**

Figure 6 shows the average uncured resin percent for 2:1 and 15:1 resins measured in the lower, middle and upper sections of the bolt for both 28 mm and 30 mm internal diameter pipe installations. The highest proportion of uncured resin was observed in the upper 300 mm of both resin types. The results show a higher average percentage of uncured resin in the 15:1 resins across the entire length of the resin anchor. The results also show a trend of an increasing proportion of uncured resin toward the upper portion of the bolt.

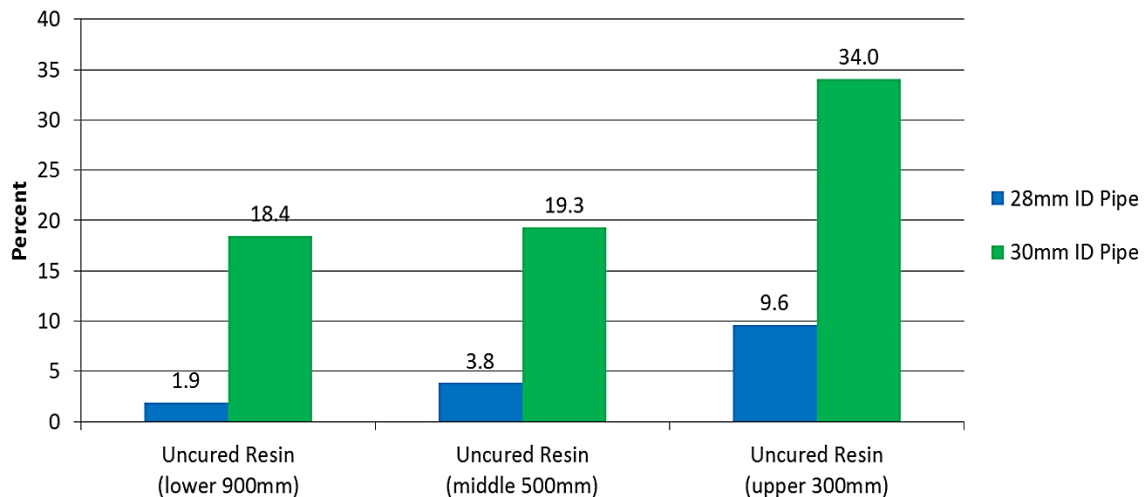


**Figure 6 - Average percentage uncured resin observed for 15:1 and 2:1 resins by lower, middle and upper bolt sections**

Figure 7 shows the separation of the 15:1 data into 28 mm and 30 mm internal diameter pipe installations. The averages show an increasing percentage of uncured resin toward the upper end of the pipe in both 28 mm and 30 mm pipe. Significant variability was found in the range of uncured resin in the upper 300 mm. The maximum length of uncured resin was 170 mm in 28 mm pipe, and 240 mm



in 30 mm pipe. Uncured resin was observed in 50% of 28 mm pipes, and 86% of 30 mm pipes. This data shows that 15:1 resin systems become increasingly susceptible to uncured resin as the hole diameter was increased.



**Figure 7 - Average percentage uncured resin observed for 15:1 resins by lower, middle and upper bolt sections in 28mm and 30mm ID pipes**

## DISCUSSIONS AND CONCLUSIONS

The surface installation method of borehole sleeving was found to allow reliable, repeatable and standardised testing of resin-anchored bolt installations. A large number of tests was possible during a day of testing and the removal of the PVC sleeve allowed a comprehensive visual inspection of the resin annulus. The method was found to be relatively inexpensive compared with both underground installation trials, and tests using grout-filled pipes.

The primary purpose of the new methodology was to provide a highly visual analysis of resin mixing effects. However, two constraints arose. Firstly, the new methodology could not be used for load transfer assessments – due to the comparatively weak mechanical properties inherent with plastic materials. However, load transfer was not the intended purpose of this experiment.

The second constraint was that of borehole-surface effects during resin mixing. A rougher borehole will naturally enhance fluid shear in resin mixing due to the micro turbulence created by the relative roughness in the borehole surface. The plastic sleeve has a comparatively smooth surface, so theoretically, micro turbulence effects would be reduced at the borehole wall. However, the greater contribution to mixing turbulence was actually from the bolt rib profile, due to the high speed cyclic pumping action generated by rotation of the ribs at approximately 600 rpm. The test results inherently confirmed the substantial contribution of the bolt ribs in generating mixing turbulence. While the plastic sleeve might not be fully representative of borehole roughness underground, the sleeve provided a standardised and repeatable environment for comparative testing.

The implications of high insertion pressure are significant for a mining operation. Results of the current study confirmed that high pressure was developed during resin bolt installation, but was subject to varying resin annulus thickness. The maximum installation pressure was approximately 18 MPa in a 28 mm diameter pipe and was present during the upper 500 mm of the bolt travel. The results also indicate a reduction in the peak pressure to 14 MPa in 30 mm diameter bore, which was only generated during the upper 100 mm of bolt travel. The installation pressure results were very similar for both the 15:1 and 2:1 resin types tested.

The magnitude of pressure in each case would theoretically be sufficient to cause hydraulic fracturing of weak roof types, and to initiate crack development along existing planes of weakness such as bedding planes, coal cleat or rock joints. This finding supports the evidence of hydraulic fracturing and resin injection found in previous studies that used overcoring (Campbell and Mould, 2003; Compton and Oyler, 2005; Craig, 2012).

The implications of hydraulic fracturing are significant and include artificial damage to the roof and increased resin loss. Both Giraldo *et al.*, (2006) and Craig (2012) found that increasing the annulus area resulted in a reduction in resin loss. Although each mine site is subject to individual factors, the results indicate that the potential for hydraulic fracturing and resin loss is reduced by using a larger diameter bore. This is reasonable because the drill hole volume is larger for the same volume of resin. Hence, the onset of elevated pressure is delayed until later in the bolt travel toward the back of the hole. Further, the larger bolt annulus allows the resin to pass along the bolt more readily, this being the effective "relief valve" that limits peak back pressure development.

The use of a larger resin annulus has two potential benefits. Firstly, more resin will remain in the borehole with an associated greater likelihood of achieving theoretical full resin encapsulation. Secondly, a smaller area of the bolted interval will be subject to the potentially negative effects of elevated resin back pressures and associated potential for hydraulic fracturing damage. While the load transfer downside of a larger diameter hole is duly noted, it is offset to a large degree if a substantial portion of the bolt is not encapsulated. This finding provides an incentive for industry to develop a bolting system that combines high load transfer properties with the reduction in pressure inherent in using a slightly larger annulus.

Occurrence of uncured resin were observed on 1.8 m long roof bolts installed with 1000 mm long resin cartridges in both 28 mm and 30 mm diameter bores. The results show that the average percentage of uncured resin along the entire encapsulated length of both 28 mm and 30 mm bores was 10.6% for 15:1 resins, and 0.4% for 2:1 resins. Based on this finding, the use of 2:1 resins could offer a significant improvement in roof bolt effectiveness.

A potential reason for the broad difference in uncured resin percentages was the size of the limestone filler. The 15:1 resin was characterised by smaller limestone fragments than the 2:1 resin. The larger limestone filler in the 2:1 resin was clearly observed to scour the internal surface of the PVC pipe. This scouring was not seen on the inside of the 15:1 resin pipes. It is reasonable to suggest that the larger filler particles cause a greater degree of friction and shearing of the fluid during bolt rotation, contributing to a more uniform resin mix. In combination with the higher proportion of catalyst, the difference in filler may explain the reduced potential for uncured resin observed in the annulus of 2:1 resins.

For both resin types in both bore diameters, the highest percentage of uncured resin was observed in the upper 300 mm of the bolt. The percentage of uncured resin was 16.8% in the 15:1 resin samples, and 0.8% in the 2:1 resin samples. Therefore, the 2:1 resin can be concluded to be a more robust resin anchor with regard to curing in the critical top 300 mm for both 28 mm or 30 mm bore diameters, in the context of this study. This finding has substantial implications for the development and use of roof bolt pre-tensioning. Pre-tensioning is highly reliant on a consistent anchor being generated at the top of the bolt as soon as the fast set resin cures. With a highly reliable anchor at the top of the bolt, the theoretical strata control improvements of increasing roof bolt pre-tension can be investigated with greater confidence.

When the 15:1 resin was assessed by bore diameter, a higher percentage of uncured resin was found in the lower, middle and upper portion of the bolt in the 30 mm diameter bores. Further, it was found that 9.6% of the resin was uncured in the upper 300 mm of 28 mm bores, while 34% of resin was uncured in the upper 300 mm of 30 mm bores. These findings demonstrate the sensitive link between increasing hole diameter and uncured resin for the 15:1 resins. This relationship between borehole size, resin type and installation pressure indicates further investigation is required to optimise roof bolting systems.

It is noted that there is less control available on the actual bolt hole diameter in underground conditions because of factors such as strata conditions and installation variables. Consequently, "run of mine" installations may be subject to higher percentages of uncured resin than the equivalent surface trials performed under controlled test conditions. The results of this study suggest that 2:1 resin cures more reliably over the entire encapsulated length for the two bore diameters assessed.

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